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Abstract

Purpose: Vertical-jump tests are commonly used to evaluate lower-limb power of athletes and non-athletes. Several types of equipment are available for this purpose. Here we compared the error of measurement of two jump-mat systems (Chronojump-Boscosystem and Globus Ergo Tester) with that of a motion-capture system as a criterion. Additionally we determined the modifying effect of foot length on jump height. ***Methods:*** Thirty-one young adult males alternated four countermovement jumps with four squat jumps. Mean jump height and standard deviations representing technical error of measurement arising from each device and variability arising from the subjects themselves were estimated with a novel mixed model and evaluated via standardization and magnitude-based inference. ***Results:*** The jump-mat systems produced nearly identical measures of jump height (differences in means and in technical errors of measurement ≤1 mm). Countermovement and squat-jump height were both 13.6 cm higher with motion capture (90% confidence limits ±0.3 cm), but this very large difference was reduced to small unclear differences when adjusted to a foot length of zero. Variability in countermovement and squat-jump height arising from the subjects was small (1.1 and 1.5 cm respectively, 90% confidence limits ±0.3 cm); technical error of motion capture was similar in magnitude (1.7 and 1.6 cm, ±0.3 and ±0.4 cm), while that of the jump mats was similar or smaller (1.2 and 0.3 cm, ±0.5 and ±0.9 cm). ***Conclusions:*** The jump-mat systems provide trustworthy measurements for monitoring changes in jump height. Foot length can explain the substantially higher jump height observed with motion capture.

Keywords: *motion capture, contact mat, jump performance, reliability, open source technology, modeling*

Introduction

Jump height performance can be regarded as one of the most important basic functional parameter in many different sports. Tests of jump height are used to measure lower-limb muscular power[1] as well as coordination of lower and upper extremities since maximal height is achieved when a coordinated flexion of the hips, knees and ankles is properly executed.[2] Use of a jump mat is a popular approach to measuring jump height, owing to the portability, ease of use, and low cost of this equipment. A jump mat provides an estimate of jump height calculated from flight time, which is measured via interruption of an electrical circuit when the subject's feet are not in contact with the mat. As such, the measure of jump height is indirect and needs to be validated against a criterion measure. In previous validity studies, flight time with a jump mat was compared with that of a force platform,[3–5] which itself provides only an indirect measure of jump height derived from integration of ground reaction force during the jump. It is therefore unclear whether the apparent overestimation of flight time and jump height with the jump mat in these studies translates into overestimation of true jump height.

The most direct criterion measure of jump height is derived from motion capture, in which high-speed cameras are used to estimate the center of gravity of the subject in the sagittal plane.[6,7] The aim of the present study was twofold: first, to compare jump height provided by a jump mat with that of motion capture. Two version of software were used to estimate jump height with a jump mat: a proprietary version that came with the jump mat (Globus Ergo Tester) and an open-source version (Chronojump-Boscosystem). Since these methods measure jump height from different starting positions (flat foot for motion capture and toe end for jump mat), geometric parameters like foot length may affect differences between methods.[8,9] Therefore, the second aim was analysis that included the subjects' foot length, which we surmised might account for any consistent differences in jump height between the jump-mat and motion-capture estimates. A further novel aspect was a comparison of the errors of measurement arising from the jump-mat and motion-capture systems using a linear mixed model that accounted for error arising from the subjects themselves.

Methods

Subjects

The 31 male subjects recruited for this study were active sportsmen in various disciplines. Subjects were instructed not to drink alcohol or caffeinated beverages for 24 h before testing. All jumps were performed by each participant at the same time of the day to eliminate effects of circadian rhythm. The study protocol conformed to the guidelines of ethical principles of the Declaration of Helsinki. All participants signed the informed consent after having understood the aims and risks of the study.

Methodology

The study was observational, consisting of repeated measurements on subjects during a single testing session. The tests started with standardized warm-up period of 5 min on a cycle ergometer set up at 80 W power load. The subjects then performed several familiarization jumps on the jump mat followed by eight repetitions of alternating squat jumps and countermovement jumps (four countermovement jumps and four squat jumps in total) with a rest period of 1 min between jumps. Half the subjects started the alternating sequence with squat jump and the other half with countermovement jump. For countermovement jump, subjects flexed knees to an angle of 90° and jumped as high as possible in a single movement. For squat jump, they flexed knees again to 90°, held this position for 5 s, then performed the jump after an acoustic signal without any countermovement. Knee right angle was controlled by real-time video analysis in the sagittal plane through digitizing software. Subjects were instructed to repeat any jump performed incorrectly if they failed to follow the above guidelines. For both type of jump, arms were in a steady position with hands on hips.

All trials were recorded simultaneously with motion-capture and jump-mat systems. The motion-capture system (Optitrack Motive, Oregon, USA) consisted of eight cameras tracking body markers in a 4 x 4 m capture area. The markers were reflective spheres without wires to minimize interference in the movement of the athlete. Each camera was paired with 64 infrared lights in a ring configuration around the lens as the markers were able to reflect light back in the direction from which it came. The eight cameras were synchronized at 100 Hz, 20 µs shutter speed to achieve 3-D tracking with 1 mm resolution. The Helen Hayes-Davis marker set (HH) was used to follow center-of-gravity displacements.[10] Jump height was given by the difference between the sacrum marker height in upright position before execution and the apex of the airborne phase.

The jump-mat systems were a commercial model (Globus Ergo Tester, Codognè, Italy) and an open-source hardware and software model (Chronojump-Boscosystem, Barcelona, Spain). Each system consisted of a rigid 60- by 42-cm contact mat made of two isolated electrical plates in an open circuit configuration that is closed when a subject stands on the mat. The mat was connected to a handheld microcontroller (Globus) or computer (Chronojump), which computed and stored flight time with a temporal resolution of 1 ms. The displacement of center of gravity (jump height h) during flight was estimated by means of flight time through a standardized kinematic equation $h=t^2 \cdot g/8$, where g is the gravity acceleration (9.81 m/s^2).[11]

Simultaneous use of both mats, either by placing one on top of the other or by placing them side by side, resulted in different time activations. We therefore tested the subjects with only one mat connected via an electric T-junction to the microcontroller and computer. Any differences in jump height were therefore due to software. Foot length was measured directly by digital evaluation of the foot print by means of a 2-D foot scanner (Sensormedica, Rome, Italy).

Statistical Analysis

Two mixed linear models, realized with Proc Mixed in the Statistical Analysis System (version 9.4, SAS Institute, Cary NC, USA), were used to analyze jump height. The first mixed model was a straightforward reliability analysis to show that the jump-mat produced almost identical outcomes with the two versions of software. The fixed effects were the jump attempt and the identity of the software (both nominal effects without interaction, to estimate the means for each jump and the mean difference between the two versions of software). The random effects were the identity of the athlete (to account for repeated measurement of the athletes, by estimating their means), the interaction of jump attempt with identity of the athlete (to estimate the random error arising from the athlete on each jump), a dummy variable for the Globus interacted with jump attempt (to estimate additional random error of measurement associated with the Globus on a given jump), and the residual random error on every measurement. Separate analyses were performed for countermovement and squat jumps. The second mixed model was adapted from the first to compare reliability of the jump-mat systems with that of motion-capture. The fixed effects were jump attempt, identity of the system (Chronojump, Globus, motion-capture), and the interaction of the identity of the system with foot length (to estimate and adjust for the modifying effect of foot length on jump-mat and motion-capture estimates of jump height). The random effects were the identity of the athlete, the interaction of jump attempt with identity of the athlete, a dummy variable for the Globus or Chronojump interacted with jump attempt (to estimate an additional single value of random error associated with the Globus and Chronojump on a given jump attempt), a dummy variable for motion-capture interacted with jump attempt (to estimate additional random error associated with motion-capture on a given jump attempt), and the residual. The square root of the sum of residual and device variance gave an estimate of the technical error of measurement for each device. The technical errors were compared with a spreadsheet.[12] Technical-error variance and within-subject variance were combined similarly to give estimates of observed jump-to-jump error of measurement. Separate analyses were again performed for countermovement and squat jumps.

Magnitudes of differences between means were evaluated using standardization by dividing the difference by the between-subject SD given by the random effect for athlete. The magnitude of the effect of foot length on jump height was evaluated as the standardized difference in the mean jump height of subjects differing by 3 cm (approximately 2 SD of foot length). Threshold values for assessing magnitudes of standardized effects were 0.20, 0.60, 1.2, 2.0 and 4.0 for small, moderate, large, very large and extremely large, respectively. Magnitudes of error were also assessed by standardization, but the thresholds are half those of differences between means.[13] Uncertainty in the estimates of effects was expressed as 90% confidence limits and evaluated with magnitude-based inference.[14,15]

Results

Descriptive statistics of the subjects and the jump heights are presented in Table 1.

In the reliability analysis comparing the Chronojump and Globus systems, the between-subject SD given by the random effect for athlete was 6.2 cm for countermovement jump and squat jump, making a smallest important difference in jump height of 1.2 cm. The differences between the Chronojump and Globus means for the countermovement jump and squat jump were clearly trivial (0.1 cm, 90% confidence limits < ±0.1 cm). The random error for the Chronojump in the countermovement jump was also clearly trivial (0.2, ±0.3 cm), and the Globus had only a clearly trivial additional error (0.1, ± 0.4 cm). The random error for the

Chronojump in the squat jump was below the limit of estimation (0.0, ±0.0 cm), and the Globus had only a clearly trivial additional error (0.1, ± 0.1 cm).

Owing to the trivial differences between the Chronojump and Globus, their random effects were combined for the reliability analysis, and the resulting standard deviations representing between-subject differences, within-subject variability, and errors of measurement are shown in Table 2. Most standard deviations were small, but the technical error for the jump mats was trivial, and the jump-to-jump standard error of measurement that would be observed with motion capture was moderate. The technical error with motion capture was possibly larger than that with the jump mats for countermovement jumps and likely larger for squat jumps.

Motion capture produced clearly larger mean jump heights than those of the jump-mat systems for countermovement jump (by 13.4, ±0.3 cm) and squat jump (by 13.6, ±0.2 cm), both very large differences. The effects of 3 cm (~2 SD) of foot length were trivial but unclear for jump-mat (-0.7, ±4.2 cm) and motion-capture systems (0.7, ±4.2 cm) for the countermovement jump and squat jump; however, the difference between these effects (1.4, ±0.5 cm) was small and likely substantial. Consequently the very large differences between the motion-capture and jump-mat systems reduced to small differences when adjusted to a foot length of zero, but the difference was unclear for the countermovement jump (-2.6, ±5.9 cm) and squat jump (1.6, ±4.4 cm). These data are consistent with the possibility that the difference in jump height between the motion-capture and jump-mat systems is explained entirely by foot length.

The equation for predicting mean motion-capture height (in either countermovement jump or squat jump) from mean jump-mat height is given by motion-capture height = jump-mat height + 0.523*(foot length). Analysis of the individual differences in the actual and predicted motion-capture heights showed that the bias in the predicted jump height was 0.0

cm (90% confidence limits ±0.6 and ±0.4 cm for countermovement jump and squat jump respectively), while the standard errors of the estimate were respectively 1.9 cm and 1.4 cm (90% confidence limits ×/÷1.24).

Discussion

The aim of the present study was to compare jump height of two jump-mat systems with that of motion-capture system as gold standard. Secondly, we analyzed subjects' foot length as a factor that might account for any consistent differences in jump height between values from jump-mat and motion-capture devices.

A novel aspect of this study was the partitioning of variability of jump performance into two sources: error contributed by the method of measurement, and variability arising from the subjects themselves, the within-subject random error. Error contributed by the jump mats in the countermovement jump appeared to be somewhat greater than that in the squat jump (1.2 vs 0.3 cm), but given the uncertainty in the estimates of the errors (±0.5 and ±0.9 cm), and the lack of any obvious reason why they should be different, the errors are probably similar in magnitude. On the other hand, errors produced by motion capture were possibly or likely larger for the countermovement jump and squat jump (1.7 and 1.6 cm). In this study, we used the Helen Hayes-Davis marker set, which is based on the assumption that motion of the pelvis is representative of the total body center of mass. Approximating total body center of mass motion without a whole-body marker set may be the cause of the larger errors.[16] In fact, Kibele[6] reported a 7 cm difference between stand-up position and the inflection point of the countermovement due to flexibility of the S-shaped spine. Moreover, in a properly executed jump, the orientation of the body segments during upright position and the jump apex is approximately the same, but in inexperienced jumpers the excursion of the total body center of mass and pelvis during jump show differences,[17] and even jumpers with prior training land with their bodies partially crouched.[18]

The difference in the within-subject random error between countermovement jump (1.1 cm) and squat jump (1.5 cm) might be explained by differences in the technical execution of each jump. The countermovement jump is a natural movement, and all participants were familiar with its execution, whereas some participants were probably unfamiliar with the squat jump and performed slight counter movements. However, the observed variability in jump performance given by combining the within-subject error and the error contributed by the method of measurement were very similar, so from a practical perspective there is no substantial difference in the errors with two modes of jumping. The observed variability with motion capture was marginally greater than with the jump mats.

The observed error of measurement for the jump-mat system in countermovement jump in our study (1.7 cm) is comparable with or slightly lower than errors for jump mats reported in other reliability studies with similar subjects: 1.7 cm,[19] 1.8 cm,[20] and 2.4 cm.[21] A smaller error of 1.2 cm was reported by Aragon,[22] who calculated jump height from flight time obtained from the vertical ground reaction force measured with a force plate. In the only reliability study of countermovement jump using a video method, Aragon[22] reported an error of measurement of 1.3 cm. We have been unable to find studies reporting error of measurement for squat jump.

There was a considerable difference in mean jump height between the jump-mat and motion-capture systems for the countermovement jump (34 vs 48 cm) and squat jump (33 vs 46 cm). These differences are similar to those of previous studies, such as Aragon,[22] where mean jump heights measured with a jump mat and motion capture were 40 cm and 52 cm. Dias et al.[18] reported a similar difference. Some studies suggested that jump height could be dependent on landing technique but final results were questionable[8] or there was no correlation between foot geometry and between diverse values of jump height derived from different measurement devices.[9] A novel approach in our study was to take foot length into account in the analysis of jump height, and we found that the very large difference between the motion-capture and jump-mat systems was reduced to a small difference when we adjusted to a foot length of zero. Although these differences were unclear both for countermovement jump and squat jump, the finding is consistent with the difference in jump height between the two systems being due entirely to the length of the foot. Linear regression equations have been proposed for predicting the countermovement jump from jump mats with various reference methods, such as 2D[18] and 3D video systems,[22] jump-and-reach tests,[8,23] or force plates,[3,4,24–26] but in the only study using a comparable video system, Dias et al.[18] found a standard error of estimate of 1.2 cm. Even though our prediction error is somewhat greater (1.9 cm), the advantage of using an equation that adjusts for foot length is that the equation may be independent of the jumping ability of the subjects, whereas a regression equation that links only the jump heights may be specific to the population from which the sample was drawn and may not apply with the same accuracy to other populations.

Practical implications

Practitioners can be confident about using a jump mat to monitor an athlete's counter-movement or squat-jump height, because the measurement error is marginally less than that with a less convenient criterion method based on motion capture. Jump height with the jump mat is substantially less than with motion capture, owing to the role of foot length in the flight time used to calculate jump height off the mat. A simple equation incorporating foot length can be used to predict criterion jump height from jump-mat height, but further research is needed to determine whether a single equation can be applied to different athlete populations.

Conclusions

There were negligible differences in error in jump height estimated from commercial and open-source versions of software for estimating jump height from flight time measured with a jump mat. The error in jump height with the jump-mat systems was marginally less

than that with a criterion motion-capture. The substantial difference between jump height with the jump-mat and motion-capture system is explained at least partly by the modifying effect of foot length. We conclude that a jump-mat system provides trustworthy measurements for monitoring changes in jump height.

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Table 1: Subject characteristics and jump heights for the jump mats (chrono, Globus) and motion capture. Data are mean ± SD (n=31 for subject characteristics; n=121[a] for jump heights).

Age (y)		22.8 ± 4.7
Height (cm)		1.78 ± 0.08
Weight (cm)		74.6 ± 8.0
Foot length (cm)		25.8 ± 1.4
Countermovement jump height (cm)		
	Chrono	34.3 ± 6.4
	Globus	34.2 ± 6.4
	Motion capture	47.7 ± 7.0
Squat-jump height (cm)		
	Chrono	32.5 ± 6.3
	Globus	32.5 ± 6.3
	Motion capture	46.1 ± 6.7

[a] From the total number of 124 jumps, 3 were excluded (standardized residuals >4.0).

Table 2: Standard deviations (SD) representing pure between-subject differences, pure within-subject jump-to-jump variability, technical errors arising from the jump-mat and motion-capture systems, and the observed jump-to-jump error of measurement.

		SD, ±90%CL	Magnitude[a]
Countermovement jump			
	Pure between-subject differences	6.3, ±1.4	-
	Pure within-subject variability	1.1, ±0.3	small
	Jump-mat technical error	1.2, ±0.5	small
	Motion-capture technical error	1.7, ±0.4	small
	Observed jump-mat error	1.7, ±0.4	small
	Observed motion-capture error	2.0, ±0.4	small
Squat jump			
	Pure between-subject differences	6.3, ±1.4	-
	Pure within-subject variability	1.5, ±0.3	small
	Jump-mat technical error	0.3, ±0.9	trivial
	Motion-capture technical error	1.6, ±0.3	small
	Observed jump-mat error	1.5, ±0.5	small
	Observed motion-capture error	2.2, ±0.3	moderate

±90%CL, 90% confidence limits in ± form.

[a]Magnitude of the sample SD in relation to thresholds for small and moderate of 0.6 and 1.9 cm respectively (0.10 and 0.30 of the pure between-subject differences). Range in magnitude represented by the confidence limits was small to moderate for most SD.